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Snow-cover regime in Lithuania, Latvia and Estonia and its relationship to climatic and geographical factors in 1961–2015

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This study used long-term snow cover data from the Baltic States (Lithuania, Latvia and Estonia) to analyse changes in the snow cover regime from 1961 to 2015. The analysis included snow cover duration and maximum snow depth and their relationships with air temperature, precipitation and geographical factors. The longitude and elevation had the greatest impact on the spatial distribution of analysed snow parameters, whereas the air temperature had the highest impact on the snow cover duration and snow depth. During the investigation period, the decrease in the number of days with snow cover was determined. Statistically significant changes were only detected in 35% of measurement sites, mostly in the southern part of the region. The largest changes of snow cover duration were observed in December and March, while a significant trend for the entire investigation area was only recorded in April. The maximum snow depth values remained almost unchanged during the analysed period.

Introduction

Snow cover influences Earth's surface energy fluxes and regulates climate processes, mostly through the snow albedo effect. A decline in snow cover and sea ice tends to amplify regional warming (Armstrong and Brun, 2008, Vaughan *et al.* 2013). Snowmelt is the main source of fresh water in some parts of the world and it is used by up to 2 billion people (Mankin *et al.* 2015). In the Baltic States (Lithuania, Latvia and Estonia), snow cover is important for water resource management, agriculture and ecosystems (Rimkus *et al.* 2014). The extent of the snow cover is decreasing in many parts of the world due to climate change (Dery and Brown 2007, Vaughan *et al.* 2013, Wegmann *et al.* 2017) and this will have effects on both human and natural systems.

The eastern Baltic Sea region is usually covered by snow during the winter season, although decreasing trends in the extent and duration of snow cover have been observed (Rasmus *et al.* 2015). Many studies in the Baltic States have focused on the relationship between the snow cover regime and large-scale atmospheric circulation (Serreze *et al.* 1997, Keršytė and Rimkus 2014). Strong westerly circulation brings com-

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paratively warm air from the northern Atlantic to the Baltic Sea region and causes ephemeral snow cover, while weak westerlies are related to the prevailing cold continental air and stable snow cover. The interannual and regional variations in snow cover are mostly determined by the atmospheric circulation (Draveniece 2009, Klavins and Rodinov 2010), and its intensity fluctuations are described by the North Atlantic Oscillation (NAO) (Kim *et al.* 2013, Rimkus *et al.* 2014, Ye and Lau 2016, Jaagus *et al.* 2017, Szwed *et al.* 2017) and the Arctic Oscillation (Cohen *et al.* 2014, Rimkus *et al.* 2014, Jaagus *et al.* 2017). The atmospheric circulation changes associated with the NAO have received particular attention, with studies indicating that positive and negative NAO correspond to decreases and increases in the snow cover parameters, respectively (Kim *et al.* 2013, Rimkus *et al.* 2014, Ye and Lau 2016, Jaagus *et al*. 2017, Szwed *et al.* 2017).

The long-term decreasing trends in the extent and duration of snow cover in northern Eurasia are mostly related to climate change and the increase in air temperature (Bulygina *et al.* 2009, 2011, Vaughan *et al*. 2013, Rasmus *et al.* 2015). Many studies have shown that the mean air temperature in the Baltic States is increasing fastest in winter and spring (Lizuma *et al.* 2007, Jaagus *et al.* 2014). The increase in mean temperature and the intensification of westerly circulation also leads to a higher amount of winter precipitation (The BACC II Author Team 2015, Jaagus *et al.* 2016).

Recent changes in atmospheric circulation, temperature and precipitation patterns are manifested in the changing spatial and temporal characteristics of snow cover. A later formation of snow cover and an earlier snowmelt have been observed, which have led to a reduction of snow cover days (Tooming and Kadaja 2006, Draveniece *et al.* 2007, Galvonaitė *et al.* 2013). In addition, there is also evidence of more frequent thaw days (Rimkus *et al.* 2014, Rasmus *et al.* 2015). These changes in snow phenology will have serious consequences on the water balance and peak river runoff in the Baltic region (Jaagus *et al.* 2017, Stonevičius *et al.* 2017). Studies performed in Finland indicated the adverse effects of climate change on snow-based winter tourism and recreation. Social impacts are also expected, including reduced well-being, erosion of the cross-country skiing tradition and economic impacts in tourism regions (Landauer *et al*. 2015).

Snow cover patterns are not only influenced by meteorological factors (i.e., precipitation, temperature, radiation and wind) but also by geographical factors (i.e. distance from the sea, altitude, etc.) and vegetative controls (Jaagus 1997, Draveniece *et al.* 2007, Galvonaitė *et al.* 2007, Tong *et al.* 2009, Zhong *et al.* 2014). Several studies showed the dependence of precipitation on landscape factors (Jaagus *et al.* 2009, Remm *et al*. 2011). Many studies have assessed the physical snowpack characteristics and its variations in different landscapes and land-cover types (Kitaev *et al.* 2002, Andreadis *et al.* 2009, Varhola *et al.* 2010, Roth and Nolin 2016).

Several national and local studies were dedicated to the temporal and spatial dynamics of snow cover in the Baltic States (Draveniece *et al.* 2007, Rimkus *et al.* 2014). The studies showed that snow cover variability was highly affected by the microclimates of subregions, while the dominant effects included distance from the sea and elevation (Jaagus 1997, Tooming and Kadaja 2006, Galvonaitė *et al.* 2007). Snow cover climatology is traditionally based on snow depth observations at meteorological stations (Tooming and Kadaja 2006, Draveniece *et al.* 2007, Galvonaitė *et al.* 2007, Rimkus *et al*. 2014); however, the main limitation of *in situ* measurements is the rather sparse national observation networks, especially on the border regions. Expanding the research area to neighbouring countries can help to fill these data gaps and provide more homogeneous data fields.

This study assessed snow climatology in the whole region, combining different data from the Baltic States. The snow cover duration and maximum snow depth were analysed and used to estimate the spatial and temporal variability of snow cover characteristics in the Baltic States over a 55-year period (1961–2015). The main objectives of this study were (1) to describe the mean snow cover regime and its spatial differences in the whole study region, (2) to classify winter seasons according to the snow cover dynamics, (3) to analyse tendencies and regime shifts in the time series of snow cover parameters, (4) to analyse the relationships between air temperature, precipitation and snow cover parameters, and (5) to analyse the geographical factors influencing snow cover parameters and to create statistical models of snow cover spatial distribution using multiple regression.

Data and methods

The investigation area is located in the eastern part of the Baltic Sea basin (Fig. 1), and it occupies an area of approximately 175 000 km^2. This is a flat region with low hills, with the highest point being only 318 m above sea level (Fig. 1). According to the Köppen climate classification, almost the entire area belongs to the same climate type, Dfb, which is characterised by humid continental climates with warm (sometimes hot) summers and cold (sometimes very cold) winters. Only some parts of the western coast belong to the climate type Cfb, which is characterised by temperate maritime climates (Chen and Chen 2013). In 1981–2010, the lowest mean monthly air temperature (usually in January or February) in the study area varied from –6.1 to –1.5 °C, while the highest mean monthly air temperature (usually in July) varied from 16.8 to 18.8 °C. The annual mean precipitation amount varied from 581 to 872 mm. The highest precipitation amount fell during the summer months (July and August) and in autumn, while the driest periods were in winter and early spring.

This study analysed two main parameters of snow cover: the duration (i.e. the number of days with snow cover) and the maximum depth. These indicators were calculated for the entire cold season (October–April) and for each separate month.

A day with snow cover was considered a day when more than 50% of the area surrounding the meteorological station was covered with snow. This condition was applied independently from the observed snow depth. Snow depth at the meteorological station was measured using a snow ruler once a day at 06:00 UTC. The maximum seasonal or monthly snow depth was the maximum daily value in this period.

Snow cover data were obtained from 57 meteorological stations between 1961 and 2015. Of the 57 stations, 21 were in Estonia, 19 were in Latvia and 17 were in Lithuania (Fig. 1). Small data gaps (accounting for approximately 0.5% of all data) were filled with data from neighbouring meteorological stations using the ratio method. Mean snow cover values were also calculated for the reference period of 1981–2010, which was considered to be a climate normal. For the reference period, average values of the entire territory were estimated for the whole cold season.

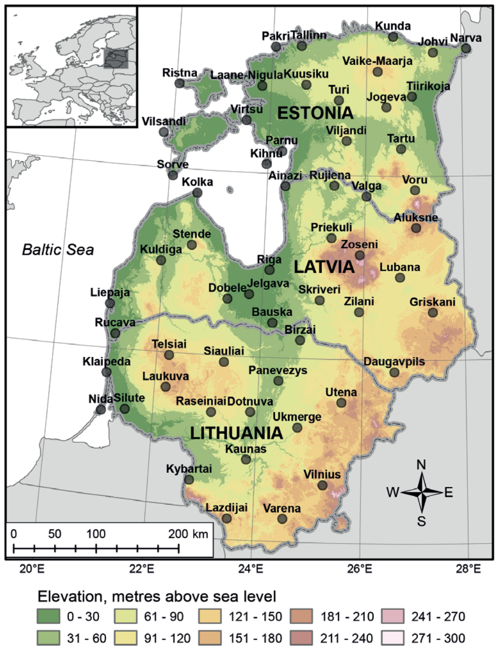

Fig. 1. Location and topography of the study region and meteorological stations.

The average monthly air temperature and precipitation amount in the analysed area during the study period (1961–2015) were derived from the CRU TS4.01 (spatial resolution 0.5° × 0.5°) dataset (Harris and Jones, 2017). Average values from the terrestrial grid cells over the study area (53°–60°N, 20°–30°E) were used in this research.

The homogeneity of data series was checked using Standard Normal Homogeneity Test (SNHT). Almost all statistically significant change-points were detected at the end of the 1980s and could be considered a result of climate regime shift in the investigated area. In the remaining cases, it has not been established that inhomogeneity could be due to the relocation of the station or the changes in the measurement methodology.

The relationship between snow cover duration and air temperature in the Baltic States was investigated in this research. The snow cover duration is most closely related with the mean air temperature in the period from November to March, while the maximum snow depth is related with air temperature during the period with the most intensive snow accumulation (December–February). All cold periods in 1961–2015 were divided into three equal groups, according to the average temperature anomaly, to compare the impact of geographical factors on the spatial distribution of snow cover in cold and warm winters.

A hierarchical clustering technique (Euclidean distance measure; complete linkage) was used to group the years with different snow cover regimes according to the distribution of monthly snow cover duration: five winter types were distinguished.

Trends in snow cover duration and maximum snow depth were estimated using the nonparametric Sen's slope method (Helsel and Hirsch 1992). The rate of change in the trends was calculated for both individual months and the entire season. The statistical significance ($p < 0.05$) of the trends was evaluated using the nonparametric Mann-Kendall test, while a sequential *t*-test analysis was used to evaluate the snow regime shifts, e.g. to detect change points in the data series.

The impact of independent geographical variables (i.e. latitude, longitude, distance from the sea and elevation) of the stations on the spatial distribution of snow cover parameters in the Baltic States were also evaluated using a linear multiple regression model in which snow cover parameters were dependent variables and the three geographical factors were independent variables.

Results

Mean snow cover regime

On average, the first temporary snow cover starts to form in the northeastern part of the region at the beginning of November, while in the coastal areas it forms by the end of that month. Generally, a permanent seasonal snow cover forms 3–4 weeks later and as snow accumulates, snow cover depth gradually increases. Usually, snow depth reaches its maximum in the second half of February or at the beginning of March. The snow starts to melt and seasonal snow cover disappears at the end of March or at the beginning of April. The interannual variability of the snow cover duration and melt time is very large; for example, in some years, snow cover persisted until the middle of April, while short-term snow events even occurred at the beginning of May. However, during the recent decades a permanent seasonal snow cover was increasingly uncommon and, in a large part of the study area, several short periods with snow cover interrupted by thaws were usually observed.

The mean snow cover duration in 1981–2010 was 93 days (Table 1). This value ranged from 56–70 days in the coastal zone in the western part of the territory to > 130 days in the northeast (Fig. 2a). The seasonal maximum snow depth varied from 15–20 cm in the coastal areas and the southwest of Lithuania to > 35 cm in the hilly upland area of the most continental part of Latvia (Fig. 2b).

The largest average snow cover duration was recorded in January, while the maximum snow depth was measured in February (Fig. 3). December, January and March were characterised by the largest interannual fluctuations in snow cover duration, while the largest fluctua-

Table 1. The mean snow cover duration (days) and maximum snow depth (cm) in the Baltic States in 1981–2010, and the Sen's slope values for 1961–2015. Statistical significance of trends (*p*) from the Mann-Kendal test.

Country	Snow cover duration/slope (days per decade)	Maximum snow depth (cm)/slope (cm per decade)
Lithuania	87.7/–4.0 ($p = 0.09$)	22.3/–0.38 ($p = 0.58$)
Latvia	93.6/–4.2 ($p = 0.09$)	25.7/–0.61 ($p = 0.53$)
Estonia	97.9/–2.7 ($p = 0.19$)	26.7/–0.32 ($p = 0.68$)
The whole area	93.4/–3.3 ($p = 0.17$)	25.0/–0.55 ($p = 0.48$)

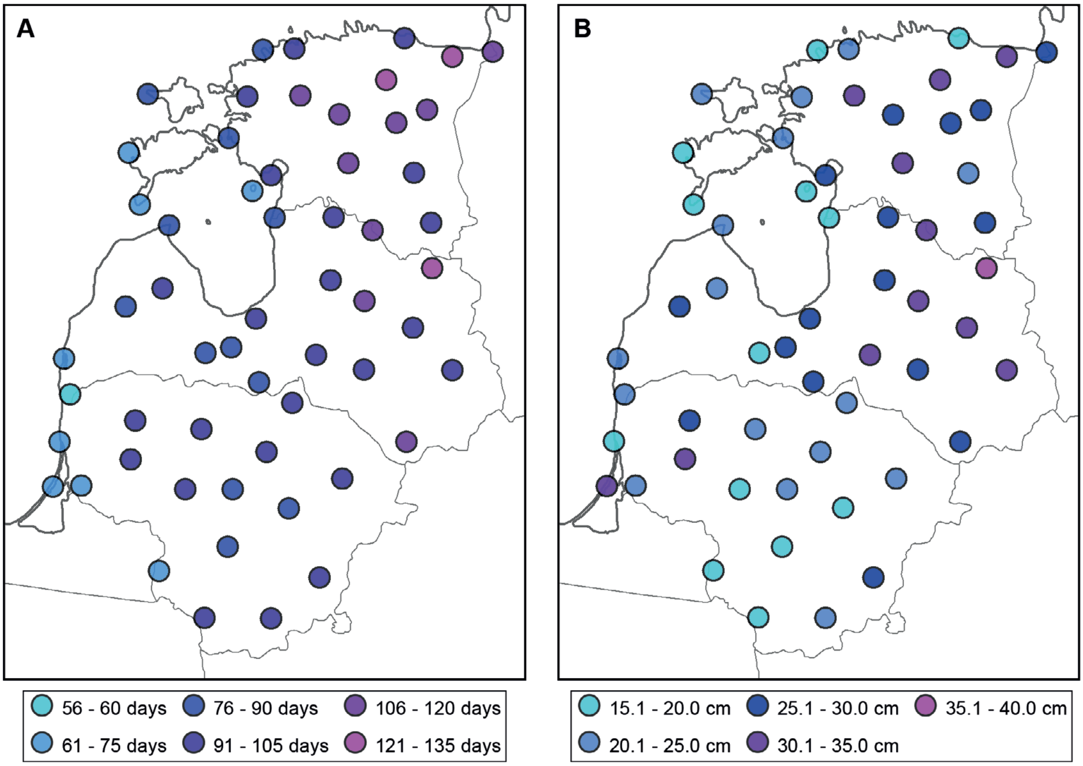

Fig. 2. (**A**) Climatological-mean (1981–2010) snow cover duration (days), and (**B**) maximum snow depth (cm) in the Baltic States.

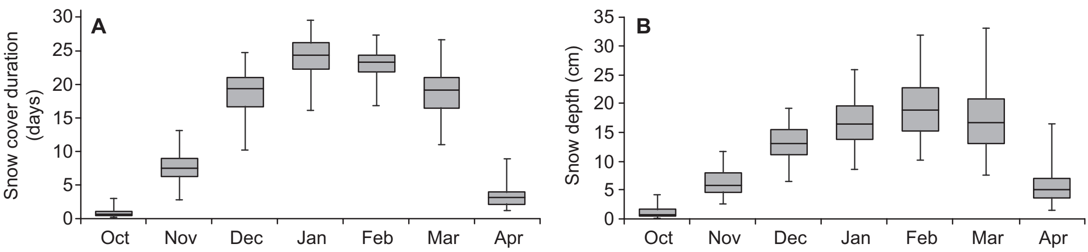

Fig. 3. Box-whisker plot (line inside the box = median box = quartiles, whiskers = maximum and minimum) of the seasonal distribution of (**A**) mean snow cover duration and (**B**) maximum snow depth in the Baltic States during 1961–2015.

tions of snow depth were determined in February and March.

Both snow indicators were closely interrelated. The correlation coefficient between the mean snow cover duration and the maximum snow depth in the investigated area was 0.77 ($p < 0.0001$). The closest connection was determined in October, March and April when the snow cover was not permanent and did not cover the whole area ($r = 0.87–0.97$, $p < 0.0001$).

Classification of winters according to the snow cover regime

The snow cover regime during all investigated winters was grouped into five types using a cluster analysis (Fig. 4). The first group was characterised by cold winters with the largest number of snow cover days and the high snow depth (Fig. 5 and Table 2). The snow cover forms in November or at the beginning of December and

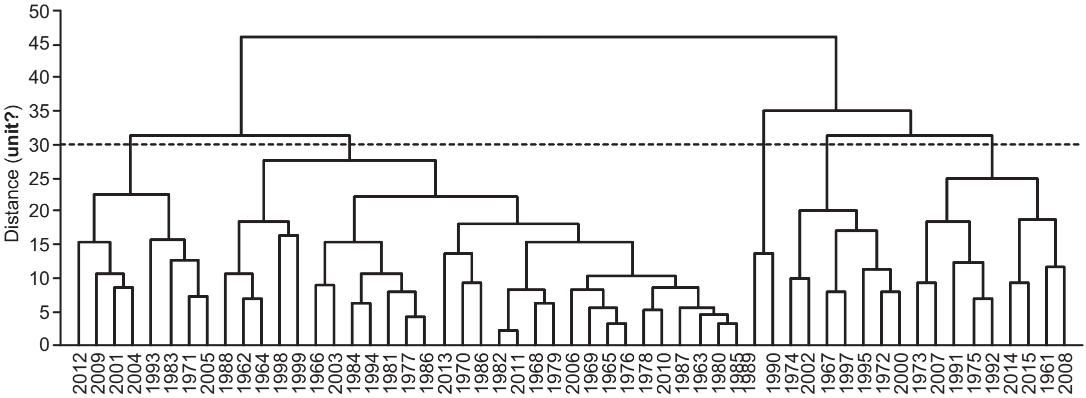

Fig. 4. Dendrogram of the hierarchical clustering of the snow cover regimes according to the distribution of monthly snow cover duration values in 1961–2015.

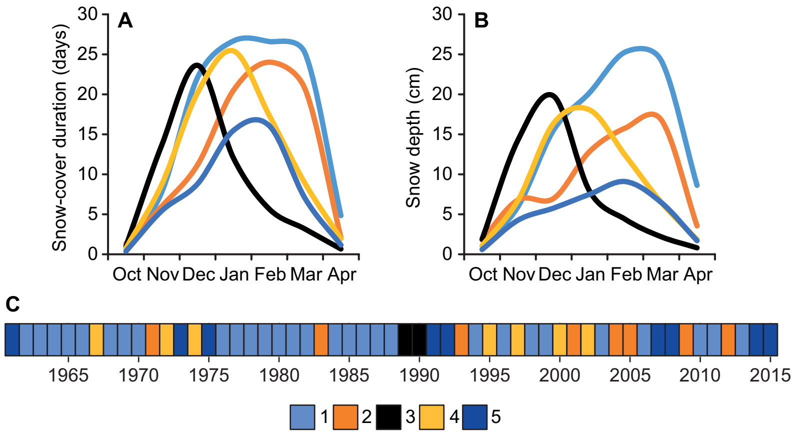

Fig 5. Different types of snow cover regime in the Baltic States in 1961–2015. (**A**) Snow cover duration, (**B**) maximum snow depth, and (**C**) temporal distribution of winter types.

stays until the end of March or the beginning of April. The second group was characterised by a permanent snow cover that formed quite late (mostly at the beginning of January) but stayed until the end of March. The third group rarely occurred (in 1989 and 1990 only) but was distinguished by an extremely early snow cover and an early maximum snow depth in December. After this early maximum snow depth, the snow cover melted, and from January to March only ephemeral snow cover formed. The fourth group was characterised by moderately snowy winters with relatively thick snow cover in December and January which thawed in the second half of the winter. The fifth group was distinguished by warm winters and thin and irregular snow cover (Fig. 5 and Table 2).

Table 2. Mean November-to-March air temperatures and frequencies of different winter types in the Baltic States in 1961–2015.

Type	Temperature (°C)	Frequency (%)
1	–3.8	52
2	–1.3	15
3	0.2	4
4	–1.6	13
5	0.1	16

Trends in snow cover parameters

The snow cover duration changed in the study area in 1961–2015 (Fig. 6a), decreasing by an average of 3.3 (p = 0.17) days per decade. The largest negative changes were observed in Latvia

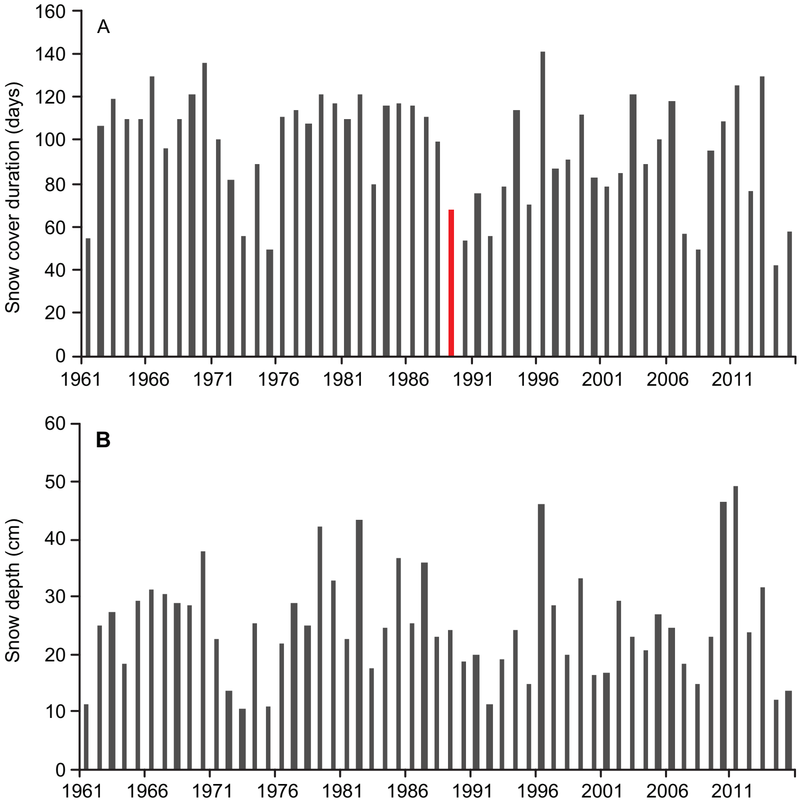

Fig. 6. Dynamics of (**A**) mean snow cover duration (days) and (**B**) maximum snow depth (cm) in the Baltic States in 1961–2015. The year of the detected regime shift in snow cover duration is marked in red.

and Lithuania, where the snow cover duration decreased by 4.2 (p = 0.09) and 4.0 (p = 0.09) days per decade, respectively (Table 1). Due to the large interannual variability, the changes in the entire area were not statistically significant. Besides that, the changes were not constant. A significant downward regime shift in this parameter was detected in 1989. The highest snow cover duration (138 days) averaged over the whole study area was recorded in the winter of 1995–1996, while the lowest snow cover duration of 42 days was recorded in 2013–2014. A decreased snow cover duration was observed at almost all meteorological stations (Fig. 7a); however, a statistically significant change was only detected in 35% of measurement sites. The greatest negative changes were identified in the southeast of the region, around the Gulf of Riga, and in some stations in Estonia.

The maximum snow depth in the study region remained almost unchanged (Fig. 6b); however, its interannual fluctuations increased in the second half of the study period. The sign of changes of maximum snow depth varied considerably in the Baltic States, and it was difficult to distinguish parts of the region where similar tendencies prevailed (Fig. 7b). Statistically significant negative changes were only detected at one meteorological station (Väike-Maarja) in northern Estonia.

The snow cover duration generally decreased during the whole winter (Fig. 8a). The largest negative changes were observed in December and March, while the only statistically significant trend was recorded in April. The statistically significant negative regime shift in 1989 was observed in February and March.

Meanwhile, snow depth slightly increased in January, while all changes were negative in the second half of the cold season (Fig. 8b). Despite the decrease of snow depth in February and March, the seasonal maximum remained almost unchanged. This was due to the maximum snow depth being more frequently recorded in December and January in recent years. In 1961–1988, the seasonal maximum snow cover depth was

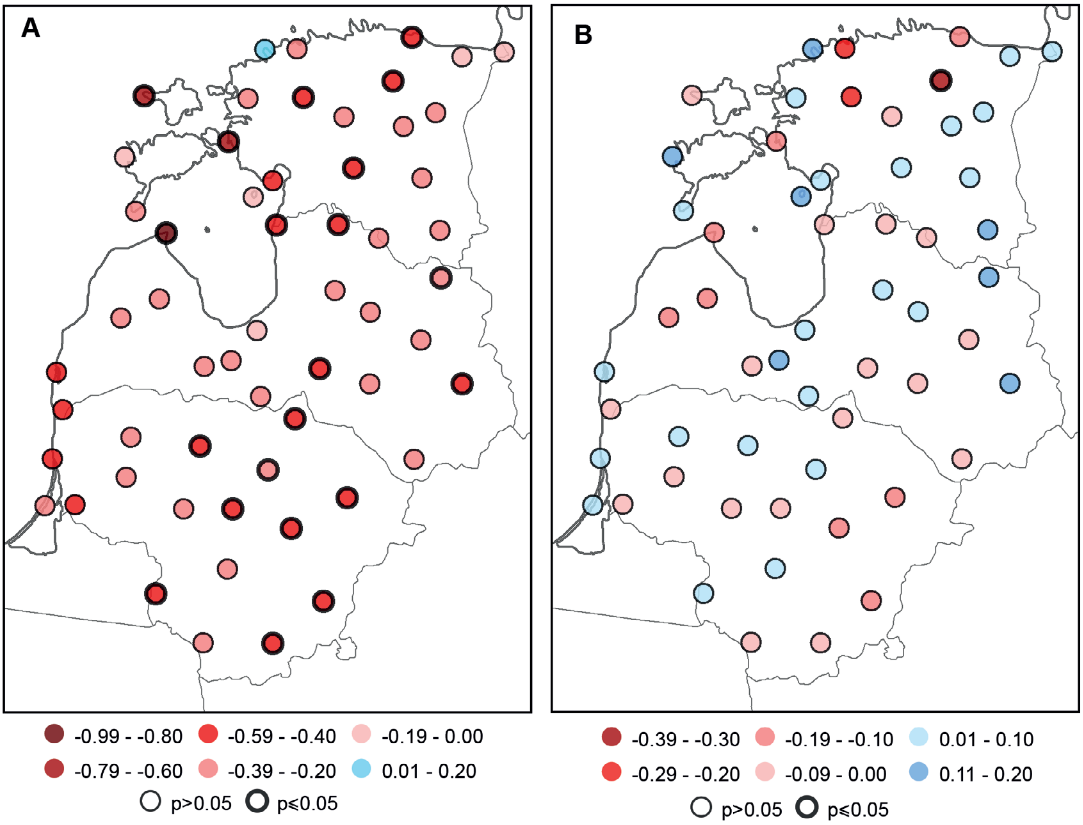

Fig. 7. Changes in (**A**) snow cover duration (days/year), and (**B**) maximum snow depth (cm/year) (Sen's slope method) at meteorological stations in the Baltic States in 1961–2015. Stations with statistically significant changes ($p \leq 0.05$) are marked with thick outlines.

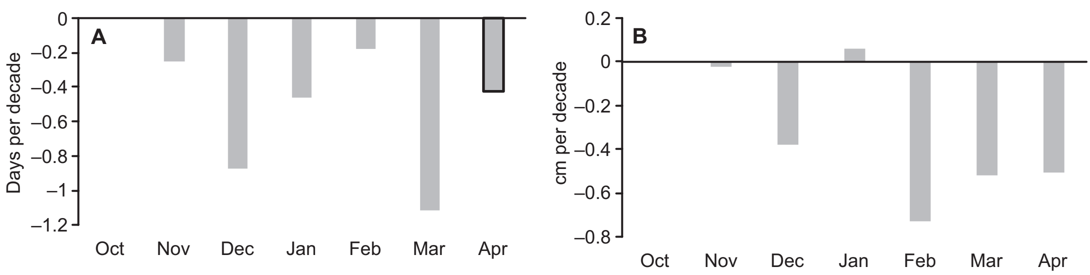

Fig. 8. Changes in the (**A**) snow cover duration and (**B**) maximum snow depth in different months of the cold season in the Baltic States during 1961–2015. Statistically significant change is marked with thick line.

recorded in December and January on three occasions, while in 1989–2015 this increased up to ten times. In winter 2012–2013, the thickest snow cover in the Baltic States was recorded in April, which was the only time this happened during the entire study period.

The snowiest period gradually shifted earlier (i.e. to January) (Fig. 9), whereas periods without snow become more frequent in the second part of the cold season. The largest decrease in the snow cover parameters was observed in March. The interannual variability of snow cover types detected using the cluster analysis also increased (Fig. 5); for example, 71% of all winters in 1961–1988 were classified as the dominant first type of snow cover regime,

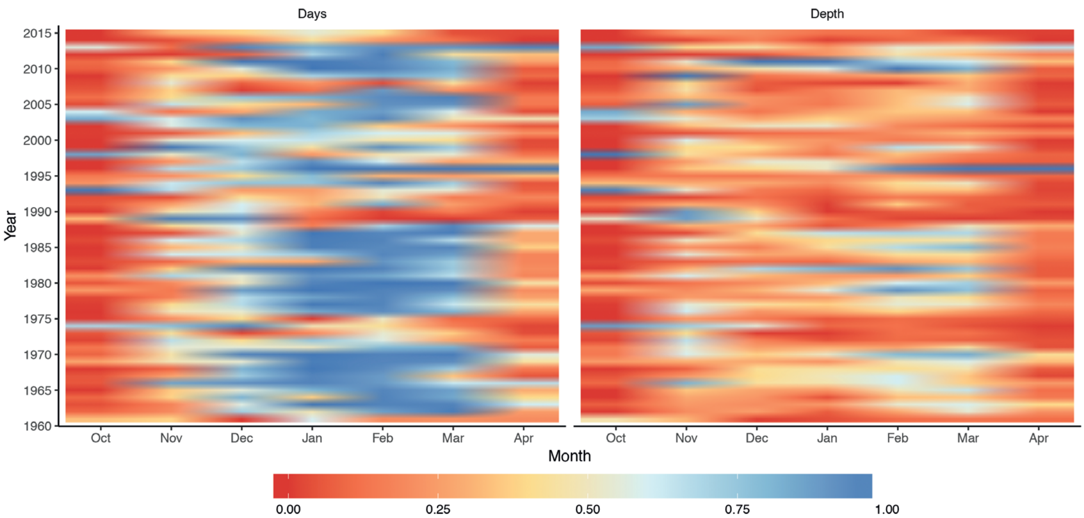

Fig. 9. Interannual and seasonal variations of scaled snow cover duration (left) and maximum snow depth (right) in the Baltic States during 1961–2015. The snow cover parameters were normalised using min-max scaling.

while in 1989–2015, the number of such winters decreased to 33%, although this remained the prevailing snow cover type.

Relationships between air temperature, precipitation and snow cover

The average snow cover duration in the analysed area was closely and negatively correlated (r = –0.94, p < 0.00001) with the average temperature in November to March (Fig. 10a). The relationship was not linear as the possible snow cover duration in this period was limited. The air temperature differences between extremely cold winters had a very little effect on this parameter.

For individual months of the cold period (November–March), correlation coefficients ranged between –0.75 (p < 0.00001) and –0.85 (p < 0.00001), while in October and April they decreased to –0.60 (p < 0.00001) and –0.46 (p = 0.0004), respectively. The average air temperature was much higher than 0 °C, and snow cover was not common in October and April. Therefore, a large air temperature interval was possible in the absence of snow cover. Precipitation did not significantly affect the snow cover duration. The statistically significant weak negative correlation (r = –0.32, p = 0.017) in February can be explained by the fact that higher precipitation amounts occur in warmer winters (r = 0.50, p = 0.0001), and this often falls in the form of rain which contributes to the snow melting.

Maximum seasonal snow depth was most closely related (r = –0.74, p < 0.00001) to the average air temperature during the snow accumulation period (December–February) (Fig. 10b). The regression was linear; however, when mean December–February temperature dropped below –4 °C, the spread of data over the regression line increased.

The relationship between the maximum snow depth and precipitation amount during the accumulation period is insignificant. In warm winters, a large part of precipitation is rain that causes snowmelt, while the positive effect of precipitation on snow depth increases during the cold winters when snowfall prevails. For individual months the correlation was also very weak. Only in October and December, statistically significant positive correlations were found (r = 0.29, p = 0.033 and r = 0.32, p = 0.017, respectively). A statistically significant positive correlation was found between the precipitation amount and the maximum snow depth during the cold winters in October (r = 0.45, p = 0.0005), December (r = 0.54, p < 0.0001), January (r = 0.27, p = 0.046) and February (r = 0.55, p < 0.0001).

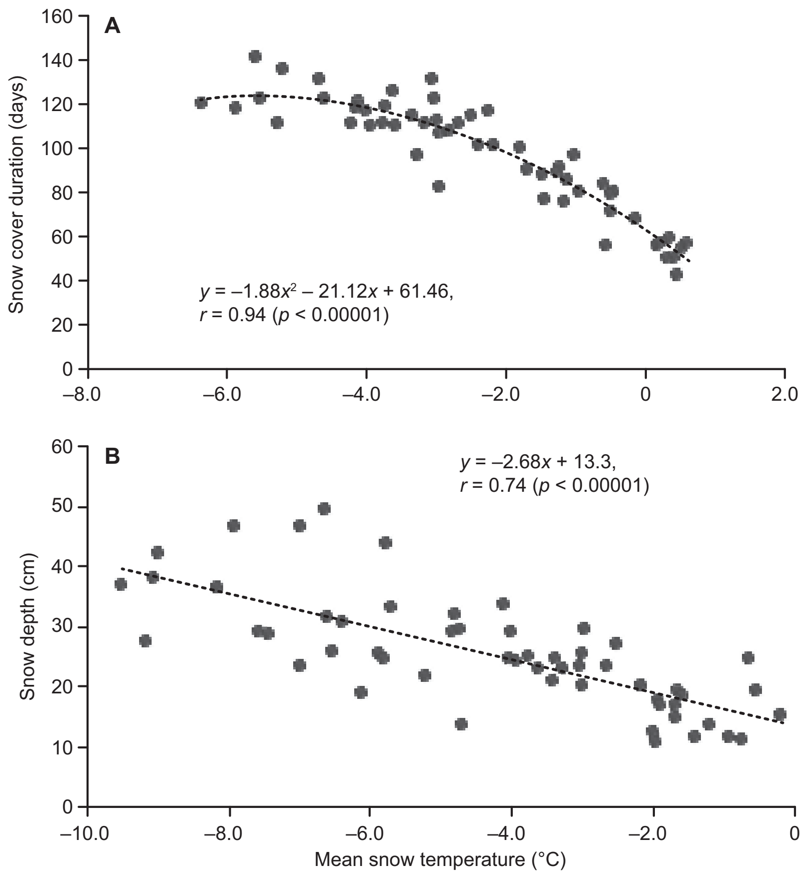

Fig. 10. (**A**) The relationship between snow cover duration and mean air temperature in November to March, and (**B**) the relationship between mean snow depth and air temperature in December to February in the Baltic States during 1961–2015.

Factors determining snow cover dynamics

During the winter, the relatively warm Baltic Sea has a significant impact on the spatial distribution of snow cover parameters. The central part of the sea is orientated in the south–north direction, and thus the longitude of a meteorological station is a good approximation of the distance to the Baltic Proper (Fig. 1). Due to the complex shape of the coastline, the distance from a meteorological station to the sea was not closely correlated to the longitude ($r = 0.41$, $p = 0.0019$). This distance to the coast had an impact on snow cover parameters from November to February (Table 3). However, the correlation was not strong, because the eastern parts of the Gulf of Finland and the Gulf of Riga are often frozen in winter and thermal contrast between the sea and continent decreases. Therefore, the snow cover duration and snow depth were relatively high in some meteorological stations located near the coast. For this reason, the stations longitude, instead of the distance to the coast, was used to assess the potential impact of the sea on snow cover parameters.

The correlation coefficient between longitude and snow cover duration was as high as 0.79 ($p <$ 0.00001). This relationship was most prominent from December to February (Table 3) when the air temperature was the lowest and the thermal contrast between the sea and land was the highest. As a result, the meridional distribution of snow cover duration can be clearly seen in these months.

The second most significant factor determining the snow cover duration was the elevation of the station ($r = 0.52$, $p = 0.00005$) (Table 3). The territorial differences in absolute height were not large (the highest measurement point in Aluksne was 197 m); however, due to the lower air temperature in higher locations, snow cover formed earlier and melted later. In uplands, snow cover was thicker and thaws were less frequent. The latitude was an important factor in October–November and March–April when a large south–north air temperature gradient developed. Conversely, the effect of the latitude on the snow cover duration was negligible in December and January.

At the beginning of the cold season, snow depth was mostly predetermined by the latitude and longitude (Table 3). In December to February, the impact of elevation increased while the influence of latitude on snow depth slightly decreased. The effect of the latitude strengthened again in March and April. The impact of the distance to the coastline on the maximum snow depth was insignificant throughout the whole winter (Table 3).

The influence of the longitude and elevation on the snow indicators increased during warm winters, and spatial differences of snow cover parameters were larger. At higher elevations and with increasing distances from the Baltic Sea (the marine air masses gradually transform by moving over the land), snow cover remained for much longer than in coastal areas. Snow cover differences between the eastern and western parts strongly increased in warm winters. In such winters, snow cover duration at some coastal meteorological stations was 70% less than in cold winters, while this value was just over 20% at some inland stations. Differences in snow depth were not so big. In warm winters, the maximum snow depth was 30%–40% lower in the outermost inland stations and 60%–70% lower in coastal stations. In cold winters, the effect of latitude on snow cover indicators became more prominent.

In order to quantify the effect of geographical parameters (latitude, longitude and elevation) on the mean spatial distribution of snow cover parameters in the analysed area, a linear multiple regression models were developed:

$$\text{SCD} = -209.3 + 3.30x + 4.42y + 0.13z, \quad (1)$$

$$\text{MSD} = -77.9 + 1.46x + 0.67y + 0.05z \quad (2)$$

where SCD is the snow cover duration (in days), MSD is the maximum snow depth (cm), x and y are the latitude and longitude (WGS 84 decimal degrees) and h is the elevation (m above sea level).

The determination coefficients (R^2) of the multiple regressions were 0.77 for the snow cover duration (Eq. 1) and 0.47 for maximum snow depth (Eq. 2). The residual standard errors were relatively small: 7.8 days for the snow cover duration and 4.0 cm for the maximum snow depth.

The analysis of model residuals was used to identify the effects unexplained by models. The largest model residuals of days with snow cover were recorded at some coastal stations (measured less than expected) where high gradients of snow parameters were present (Fig. 11). If a meteorological station is located on the coastline, the duration of snow cover can be significantly shorter than in locations a few kilometres further from the coast.

The negative residuals in the eastern part of the territory can be explained by the fact that although the longitude has the greatest impact on

Table 3. Correlation coefficients between the major geographical factors and snow cover duration/the maximum snow depth in the Baltic States in 1961–2015. Statistically significant ($p < 0.05$) correlation coefficients are shown in boldface.

Months	Latitude	Longitude	Elevation	Distance to the coastline
October	**0.47/0.49**	**0.67/0.54**	**0.36**/0.18	0.05/–0.17
November	**0.32/0.59**	**0.77/0.60**	**0.51**/0.18	**0.28**/–0.14
December	0.09/**0.37**	**0.79/0.55**	**0.59/0.31**	**0.50**/0.01
January	0.13/**0.30**	**0.81/0.52**	**0.63/0.42**	**0.51**/0.08
February	**0.34/0.37**	**0.83/0.69**	**0.52/0.49**	**0.35**/0.18
March	**0.60/0.51**	**0.77/0.74**	**0.38/0.41**	0.10/0.12
April	**0.60/0.62**	**0.54/0.61**	**0.27/0.30**	–0.08/–0.04
Season	**0.36/0.32**	**0.81/0.57**	**0.52/0.43**	**0.31**/0.10

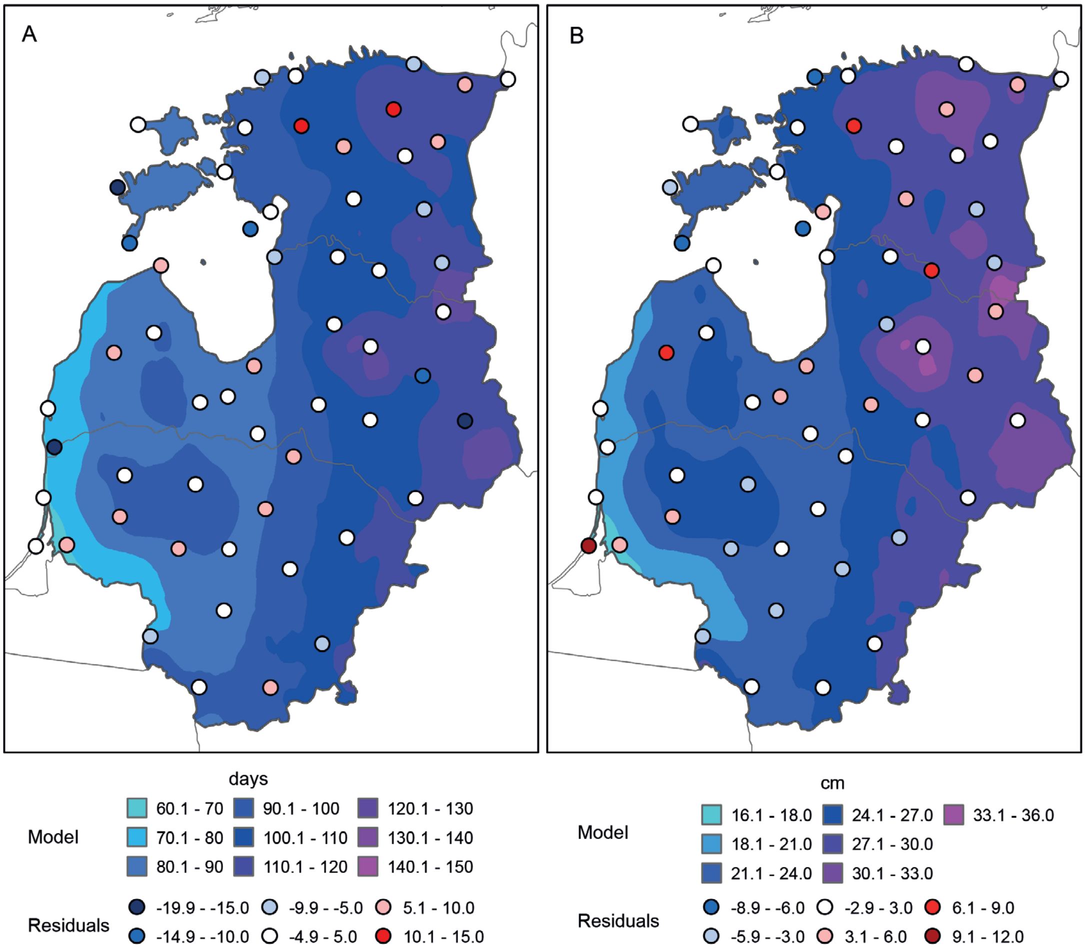

Fig. 11. The derived (**A**) snow cover duration (days) and (**B**) maximum snow depth (cm) according to the linear multiple regression model, and residuals calculated as the difference between measured and simulated values at meteorological stations.

the spatial distribution of the indicator, this effect is weaker in areas further from the sea. The non-linearity of this relationship was not evaluated in the developed model. The largest positive residuals were recorded at the two stations in northern Estonia. This suggests that the developed multiple regression model did not accurately evaluate the effect of latitude for inland stations.

In case of the maximum snow depth, the spatial distribution of residuals was not clear. Snow depth at the meteorological stations depends on local factors, such as the station environment. Point measurements at the station can be unrepresentative since the snow cover is redistributed under the local effects of the wind. The largest positive residuals in this study were recorded at the most western station, Nida, which is located in the Curonian Spit. The maximum snow depth measured there was much higher than the multiple regression model predicted. The specific conditions of the peninsula sometimes resulted in heavy snowfall during the winter (lake-effect snowstorms), which led to the formation of deep but short-lasting snow cover.

Discussion

Snow cover parameters are closely related to changes and variations in the air temperature, precipitation and large-scale atmospheric circulation. The results of this research can be added to the growing number of scientific studies that have assessed long-term environmental changes in the Baltic States.

This study detected a significant downward regime shift in the snow cover duration and a change in the dominant winter type in 1989. Jaagus *et al.* (2017) showed that there was a regime shift in the temperature, precipitation, snow cover and runoff in Estonia in the winter of 1988–1989. In their study in Poland, Szwed *et al.* (2017) also indicated that 1988 and 1989 were exceptional years in terms of their low number of snow cover days. This period was related to very high positive values of the NAO index (Rimkus *et al.* 2014) and marked a change from continental to more maritime winter conditions in the Baltic Sea region (Hagen and Feistel 2005). In later decades, the acceleration in global warming may have influenced the main changes in the snow cover parameters.

The mean winter temperature in the Baltic Sea region has increased faster than the global mean (Jaagus *et al*. 2014, The BACC II Author Team 2015). A warming trend of 0.08 °C per decade for the annual mean temperature and 0.10 °C per decade for the winter temperature was observed during 1871–2011 (The BACC II Author Team 2015). These trends in air temperature have a direct negative impact on the snow cover duration in the Baltic States. This study identified a decreasing trend in the snow cover duration of 3.3 days per decade. The trend in snow cover duration was similar to the results obtained in previous studies. For example, Jaagus *et al*. (2017) identified a decreasing trend in snow cover duration in Estonia of 3–4 days per decade and Rasmus *et al.* (2015) showed a decreasing trend in snow cover days of 2.6 days per decade for the whole Baltic Sea drainage basin. Choi *et al.* (2010) reported a decrease in the snow cover duration by 5.3 days per decade (1972–2008) in the northern hemisphere, with the most significant change during the late 1980s.

Stations with significantly decreasing trends in the snow cover duration were unevenly distributed over the entire study area; however, many were located in the southern part. In areas where the mean winter air temperature is close to 0 °C, even a small increase in air temperature can have a huge impact on snow cover. The IPCC team on cryosphere (Vaughan *et al.* 2013) showed that a decrease in snow cover was most likely to be observed at locations where air temperatures were close to the freezing point, as even small changes in the air temperature were most effective at reducing snow accumulation, increasing snowmelt or both.

The results presented here showed insignificant negative changes in the maximum snow depth values in the Baltic States during the study period. Other studies have also reported a decreasing trend. For example, Gečaitė and Rimkus (2010) found that the maximum snow depth decreased by 3.5 cm in Lithuania in 1961–2010, Bulygina *et al.* (2011) found a decrease in the maximum snow depth in the western part of European Russia and Rasmus *et al.* (2015) found that the maximum snow depth also decreased in Estonia and Poland. However, all these studies emphasised the large interannual and decadal variation in snow depth in the Baltic Sea region. This research also included newer data with maximum snow depth values (e.g., the highest values during 1961–2015 were observed in 2011) which could alter the trend values determined in the previous studies.

Despite the rise in winter air temperatures in the region (Jaagus *et al.* 2014), the thickness of snow cover decreased insignificantly. This could be explained by the fact that the average maximum snow thickness (25 cm in 1961–2015) can result within a short time frame during one or two heavy snow events and does not necessarily reflect the conditions of the entire accumulation period. In addition, the largest snowfall events are usually observed when the air temperature is only slightly below or above 0 °C. The BACC II Author Team (2015) concluded that the annual maximum ice extent in the Baltic Sea has decreased and the length of the ice season has shortened. The combination of an ice-free sea with a warm surface and outbreaks of wintertime cold air may cause intense snow showers in coastal areas (Savijärvi 2012). During these events, deep snow cover may form but it does not last long. Räisänen (2008) showed that whether the snow volume will increase or decrease during the 21st century will depend on the balance between the increasing cold season precipitation and increasing air temperature. The less-prominent snow depth changes determined in this research could be a result of balancing process described by the Räisänen (2008).

This study observed the largest changes in the snow cover parameters in the second part of the cold period. Cluster analysis showed that winters with thin and irregular snow cover became more frequent in recent decades, and that an inter-annual variation of winter types increased after the regime shift in 1989. This corresponded with the observed regional and global changes in snow cover and air temperature. The IPCC team concluded that the snow cover area, over the 1922–2012 period, decreased in most parts of the northern hemisphere, especially during the spring and autumn, due to the increase in air temperature (Vaughan *et al.* 2013). The same reason caused most of the drainage basins in the Baltic Sea region to experience an earlier snowmelt and decreased spring snow cover since 1961 (Rasmus *et al.* 2015). Bulygina *et al.* (2011) found that the spring snowmelt become shorter and more intense in the northern Eurasia. Hydrological studies in Estonia (1951–2015), Latvia (1951–2009) and Lithuania (1960–2009) showed a significantly increased river runoff in the winter months and in March due to more frequent thaws, increasing liquid precipitation and earlier snowmelt (Apsite *et al*. 2013, Stonevičius *et al.* 2014, Jaagus *et al.* 2017).

This study identified the longitude, latitude and elevation as the major geographical factors that influenced snow cover duration and maximum snow depth in Baltic States. The longitude which in the Baltic States resembles the distance from the main sea basin, together with the elevation, had the greatest impact on the spatial distribution of the analysed snow parameters. This study did not include other environmental characteristics that influence snow cover (i.e. forested areas and slope direction). A more comprehensive analysis of the effects of environmental parameters on snow cover characteristics could possibly help to evaluate the local differences in trends.

Conclusions

It is very important to analyse data from all three countries together because the relatively large study area makes it possible to highlight the impact of various natural factors on snow cover parameters and allows for evaluating the spatial distribution of snow cover indicators in border regions more precisely.

The spatial distribution of snow cover parameters in the Baltic States has a clear pattern which might be successfully quantified with linear regression models using the latitude, longitude and elevation as independent variables. The snow cover duration is longer and the maximum snow cover depth is higher in the north-eastern part of the domain. The pattern is mostly pre-determined by the proximity to the Baltic Sea.

The decrease in the snow cover duration during the 1961–2015 period was observed in all of the analysed area. The maximum snow cover thickness changed less, because the maximum snow depth in the region often can be reached during a few short-term snowfall events. Only in the northern part of Estonia, a decrease in the maximum snow cover thickness was evident. The most prominent changes in the snow cover duration were around 1989, at the same time as the type of winters changed. Before 1989, the snow cover usually formed at the beginning of winter and stayed permanent until the end of the cold season. After 1989, the warm winters or winters with a late snow cover formation and early snowmelt were observed during 16 out of 25 years.

The air temperature is the most important factor that determines snow cover duration and maximum snow depth in Lithuania, Latvia and Estonia. The prevailing type of precipitation (i.e., rain or snow) also predominantly depends on the temperature regime during the cold season. A significant positive relationship between the precipitation amount and maximum snow depth could be observed during cold winters, while in warm winters this relationship was reversed.

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